ARF

ARMOUR RESEARCH FOUNDATION OF ILLINOIS INSTITUTE OF TECHNOLOGY

ARF 5186-1
(Quarterly No. 1)

METHODS FOR PREDICTING COMBINED ELECTRONIC AND MECHANICAL SYSTEM RELIABILITY

Report No. 1

Contract No. DA 36-039 SC-90864
D. A. Project No. 3X90-90-004
First Quarterly Progress Report

1 July 1962 to 30 September 1962

U. S. Army Electronics Research and Development Agency
Ft. Monmouth, New Jersey

ARMOUR RESEARCH FOUNDATION
of
Illinois Institute of Technology
Technology Center
Chicago 16, Illinois

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The objective of this research program is to develop methods for predicting the reliability of Signal Corps equipments which make extensive use of both electronic and mechanical components.

by

Thomas L. Bush
Carlton E. Gebhart
Darwin F Simonaitis

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METHODS FOR PREDICTING COMBINED ELECTRONIC AND MECHANICAL SYSTEM RELIABILITY

I. PURPOSE

The purpose of this program is to develop methods, relationships, and/or guidelines for predicting the reliability of those types of Signal Corps equipments which make extensive use of both electronic and mechanical components. The methodology resulting from this program should be suitable for making reliability predictions during the equipments' design stage.

The steps for carrying out the program are outlined as follows:

1. Study and evaluation of the electronic reliability area, and general reliability prediction techniques
2. Development of functional module concept from equipment studies
3. Evaluation and mathematical modeling for module
4. Transformation into module probability model
5. Electro-mechanical interface considerations (combining predictions from both areas)
6. Physical model considerations, design and test of model, followed by evaluation of data and incorporation into prediction technique
7. Implementation of technique for general use in making reliability prediction

II. ABSTRACT

The major effort in the program during the first quarter was devoted to investigating the area of mechanical reliability prediction. The feasibility of a number of approaches to the mechanical reliability prediction problem was considered. The extent to which an approach based at the mechanical failure mechanism level would be applicable to the program was investigated. A survey was made of information available in the area of mechanical failure mechanisms, including such items as fracture, instabilities, creep, fatigue, wear, corrosion, etc. It was concluded that a prediction technique based at such a level would not be the most effective for the purposes of the program because of the largely empirical and qualitative nature of the information available, and because there is no generally applicable theory connecting the existing information so as to provide a unified approach for the entire spectrum of mechanical failure mechanisms. The approach selected mechanical reliability prediction is based at what is called the functional module level (an array of elements or components performing a specific function). This permits a more general approach to the problem while still allowing information to be used from lower system levels, such as failure mechanism information and any component reliability data which may be available.

III. CONFERENCES

A. Steering Committee Meeting

Date:	9 August 1962	
Place:	USAERDA, Ft. Monmouth, N. J.	
In Attendance:	H. Edelstein	USAERDA
	E. R. Fless	"
	P. E. Griffith	"
	C. Lipson	"
	H. M. Nachmias	"
	J. M. Pappas	"
	J. Sosdian	"
	R. A. Eubanks	ARF
	M. E. Goldberg	"
	G. T. Jacobi	"
	D. F. Simonaitis	"

The purpose of this first steering committee meeting was to establish final agreement between ARF and USAERDA on the over-all objectives of the program and to present the initial ARF approach. It was established that the objective of the program is to develop methods, relationships, and/or guidelines for determining the reliability of Signal Corps systems where large numbers of both electronic and mechanical components are present and where information from these two areas must be combined. A measure of comparison between different system designs would be an example of a minimum type of result from this program.

B. Inspection Visit to USAERDA

Date:	27, 28 August 1962	
Place:	USAERDA, Ft. Monmouth, N. J.	
In Attendance:	C. Lipson	USAERDA
	J. Sosdian	"
	T. L. Bush	ARF
	D. F. Simonaitis	"

The purpose of this visit was to enable ARF staff members to gain familiarity with the various kinds of electro-mechanical equipments under test and development at the Signal Corps. Various facilities at the Signal Corps were visited, including those of the Communications, Avionics, and

surveillance activities. During the visit a general picture was obtained of the various types of equipments with which the program would be concerned. Operation of a number of equipments was observed, and various displays provided an initial view of the component array within these equipments. In addition, various reports and technical manuals on these equipments were obtained. It was expected that detailed study of this literature would provide an important input to the program.

3. Steering Committee Meeting

Date:	25 September 1962	
Place:	Armour Research Foundation, Chicago, Ill.	
In Attendance:	J. Sosdian	USAERDA
	T. L. Bush	ARF
	C. E. Gebhart	"
	M. E. Goldberg	"
	A. Horberg	"
	G. T. Jacobi	"
	D. F. Simonaitis	"

At this meeting progress on the program to date was discussed. It was pointed out that a closer look was being taken at possible prediction techniques than was originally intended, particularly for the mechanical prediction task. This was being done to a large degree in place of an initial detailed survey of equipments and components as was originally outlined for the program. The literature survey of electrical/electronic reliability data had just started and would continue into the second quarter. The discussion centered upon the results of the mechanical reliability investigation. It was agreed that the investigation of mechanical failure mechanisms indicated that a mechanical predictive technique based at the failure mechanisms level would not be the most useful for the program. An initial outline was presented for a predictive technique utilizing a study of a unit or array of components called a functional module.

IV. FACTUAL DATA

A. Introduction

The title of ARF project E186, "Methods for Predicting Combined Electronic and Mechanical System Reliability," indicates the combining of information from two separate fields of interest. Thus three problem areas arise: the area of reliability prediction for mechanical objects, the area of electronic reliability prediction, and finally the problem of compatibility, i.e., combining predictions from the two areas or making an overall reliability prediction for an electro-mechanical system.

The approach as originally outlined at the beginning of program effort consisted of the following phases:

1) Signal Corps equipment survey
2) Literature review
3) Selection of composite sample system for study
4) Design and building of test system
5) Experimental evaluation of test system
6) Development of physical and reliability mathematical models for system
7) Evaluation of experimental results along with mathematical models
8) Application to complex systems

In this approach rather heavy emphasis was to be placed upon developing and evaluating some "hypothetical" electro-mechanical system whose modes of failure would be characteristic of the classes of equipment under study on this program. It was hypothesized that from a study of this system's behavior, both analytically and in the laboratory, it would be possible to develop the desired prediction technique, finally extending the technique to more complex equipments.

As work progressed, it became clear that this approach was dependent upon a higher degree of development and accumulation of data in

the area of mechanical reliability prediction than in fact exists today. There has thus been a shift in emphasis both for the quarter and for the entire program. The effort in the mechanical prediction task is being directed toward extending applicable reliability prediction techniques beyond their present limitations; the effort for the electronic portion of the prediction problem is best devoted to surveying the entire spectrum of techniques already at hand, and incorporate predictions using these existing methods with the mechanical predictions in a compatible manner.

Consideration of electronic reliability prediction has begun; effort during this particular quarter has concentrated upon the mechanical side of the interface.

B. Literature Search

The literature search being carried out for this program is concerned with surveying the existing reliability literature for information which will be useful to the program.

That portion of the survey covering the electronics and general reliability area is in progress and will be completed during the second quarter. Although the general status of electronic reliability prediction is generally well known, the information available in this area must be brought into proper perspective with regard to the entire program. The areas being investigated include reliability data, failure distributions, and the combinatorial aspect of the electronic and mechanical prediction.

A survey of current knowledge in the field of mechanical failure mechanisms was carried out, the results of which are included in this report. In addition, a request was submitted to ASTIA for a bibliography in the field of mechanical reliability. This bibliography yielded little in the way of useful information.

C. Mechanical Reliability Investigation

1. Initial considerations

The difficulties surrounding attainment of meaningful prediction techniques for the mechanical side of the interface were recognized at the inception of the program. In arriving at a realistic balance between precision of results and generalized applicability of techniques, different approaches were considered. This section discusses some of these, together with reasons for their rejection. From these considerations the program as it is now constituted was evolved.

In principle it is possible to conduct an extensive test program for various mechanical components, analagous to reliability tests performed on electronic components. Extensive tests on a single component might yield data of reasonable precision. However, the broad range of Signal Corps equipments, coupled with the time and effort required to encompass this range, precludes such an approach for this program. Equally important, however, is the extreme difficulty in extrapolating such information for prediction for components of different design under different environmental conditions. An experimental program would not provide the analytical technique suitable for broad application to mechanical reliability prediction during the equipment design effort.

As an example of this situation, failure rate data may have been compiled for a particular gear transmitting a particular torque at room temperature. The observed failures may be due to fatigue of the metal. If, to consider an extreme condition, the same gear is operated in a cryogenic environment with the same load, the failure may be of a different type (i. e., brittle fracture at peak load) making the data obtained under the

original conditions generally inapplicable. On the other hand, consider a gear similar to the first from another manufacturer operating in the original environment. It may have slightly different material properties or configuration (such as a smaller fillet radius at the bottom of the gear teeth). The failures may again be due to fatigue, but the failure rate could be radically different and unpredictable on the basis of the original data. This example generally illustrates the situation which exists for that mechanical failure data which is available. Any changes in design, material properties, environment, or application give that mechanical failure data which does exist an extremely narrow range of usefulness.

It is possible in principle to circumvent the limitations discussed above by what can be described as the determination of reliability at the failure mechanism level -- application of the fundamental laws of physics regarding changes in material properties. Here we are concerned with a detailed analysis of the design of the mechanical component. Such an analysis would then be related to a description of the part's loading and environmental history and to the known existing mathematical relationships governing the types of failure to which the part would be subject. By relating these failure relationships to time, one might then determine the various reliability parameters (such as mean time to failure) for each mode of failure of the component.

The gear mechanism previously cited will serve as a simple example. Given the environment, the load applied to the gear teeth, and the design of the gear, the stress concentration at the fillet of a tooth might be determined. Then knowing the RPM of the gear and its material, some expression relating

the stress level and the number of cycles to failure could be applied, if this expression were known. The same technique would then be applied to other possible modes of failure such as wear of the teeth, galling of the teeth, slippage of the hub on its shaft, etc.

It should be noted that herein the failure mode of a device refers generally to the gross, macroscopically observable manifestation of failure. A static failure or a corrosion failure are examples of failure modes.

The key to such a predictive technique would be to relate such failure modes, the operating stresses and environments, and the failure mechanisms.

2. Mechanical failure mechanisms study

One of the determining factors of the applicability of such a prediction technique to this program is the extent to which information is available describing such failure mechanisms. Therefore, a portion of the literature survey was devoted to this purpose. The following paragraphs indicate the kind of information and relationships generally known to govern a wide range of mechanical failure mechanisms.

a. Ductile Fracture

Ductile fracture implies a flow of the material prior to fracture. Hence, failure may result from this distortion reaching an intolerable level or from the fracture itself. The distortion is governed by the stress-strain diagram of the material involved. The shape of the curve depends on the strain hardening or the ductility of the material. Figure 1 shows a typical flow diagram. A common assumption is that an increment of strain, Δe, is proportional to the deviatory stress, s, in the component directions

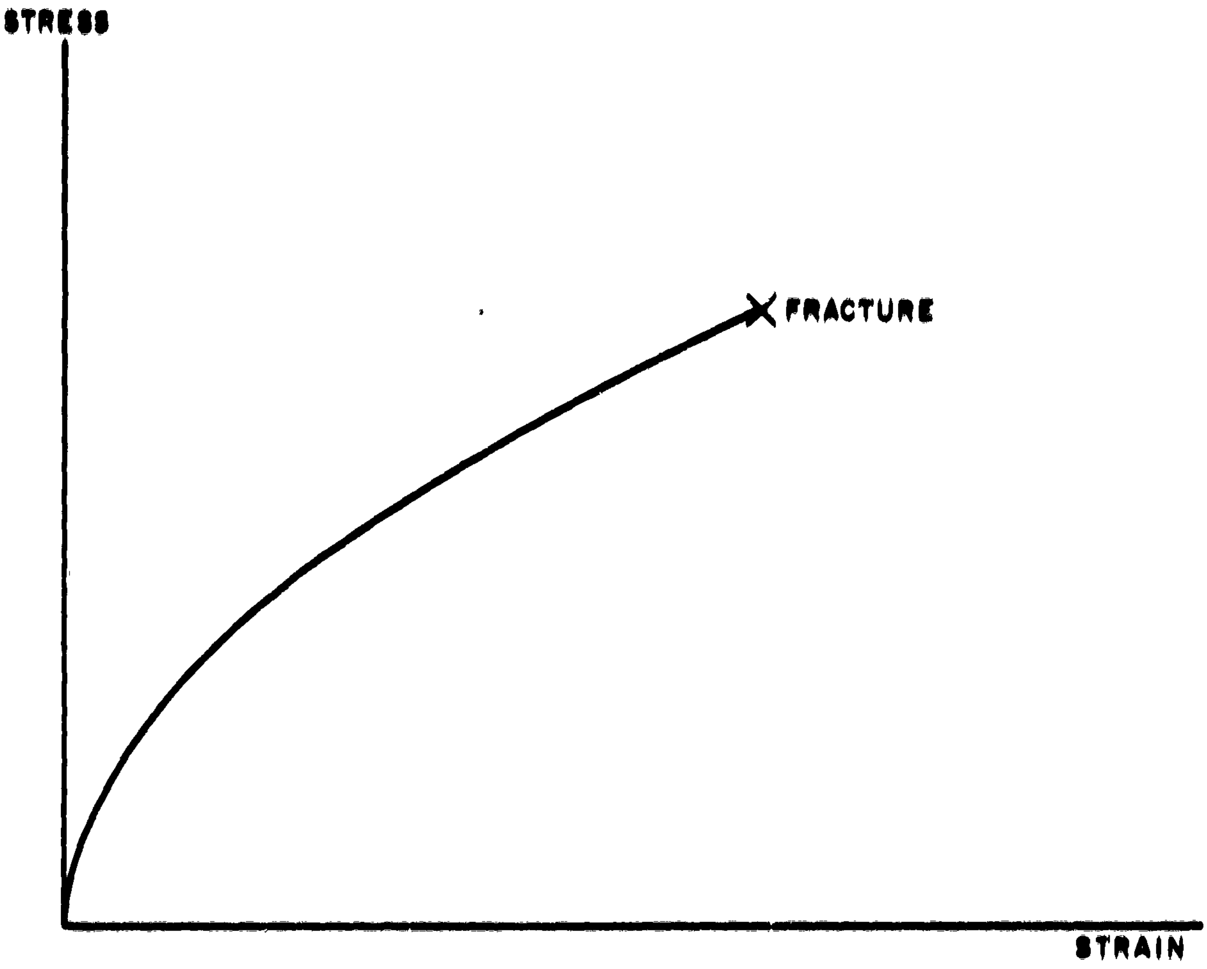

FIG. 1 TYPICAL DUCTILE FLOW DIAGRAM

(Theory by Reuss) :

$$\Delta e = ks \ . \qquad (1)$$

Final fracture depends also on the material properties, and a variety of theories are available for predicting the state at which fracture occurs. Four common theories are compared in Figure 2 for the case of biaxial stress. In this figure S'u and S''u are the tensile and compressive ultimate strengths, respectively. It should be noted that the general strength properties of a material usually decrease with increase in temperature.

b. Brittle fracture

Brittle fracture implies a rapid failure without significant prior flow of the material. The phenomenon is usually associated with an area of stress concentration such as a scratch, small pit, or crack. Most theories of brittle failure are based on the Griffith theory of crack propagation. This theory states that a crack of length 2c will propagate and create catastrophic failure when the average stress reaches the value

$$s = \sqrt{\frac{2ET}{\pi c}} \ , \qquad (2)$$

where E is Young's Modulus and T is the surface tension of the material per unit thickness. Normally ductile materials may fail in brittle manner if the temperature is sufficiently low. The critical temperature is the so-called "transition temperature."

c. Instabilities

Instabilities of components may occur whenever long and/or thin members are under compressive axial loading, torsion, and/or are rotating. Such members include shafts, bars, rings, beams, plates, tubes, and

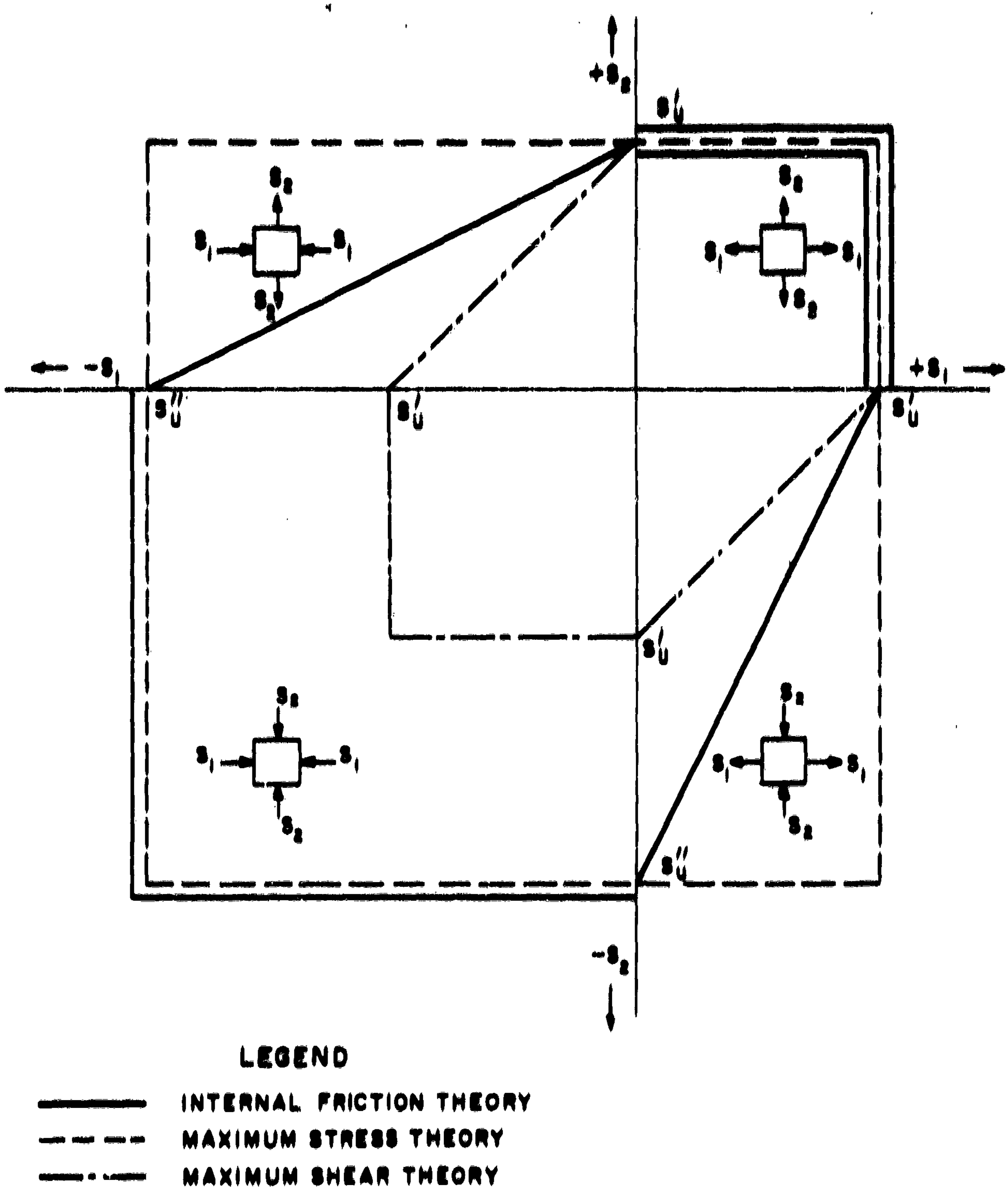

FIG. 2 COMPARISON OF FAILURE THEORIES FOR ULTIMATE STRENGTH

shells. Failure occurs when the rate of increase of strain energy of the member due to distortion exceeds the rate at which work is being performed by the loading. A simple example is a prismatic bar with comprehensive end loading which buckles when the load reaches the "Euler load" of

$$P = \frac{\pi^2 EI}{l^2} , \tag{3}$$

where EI is the modulus of rigidity and l is the length of the bar.

d. Creep

Creep is the phenomenon by which materials continue to flow even under uniform load. The distortion is generally at a very low rate but is sensitive to both stress level and temperature. Figure 3 illustrates typical constant stress creep curves.

The region of constant creep rate may generally be described by an exponential function of the stress, s, and temperature, T (Emperical relation by Bailey) as follows:

$$\frac{de}{dt} = a\ e^{bT} s^{n} , \tag{4}$$

where a, b, and n are material constants. For most engineering materials at room temperature creep is negligible below the elastic limit.

e. Fatigue

Fatigue implies the failure of a material by fracture due to repeated loading. The phenomenon may be best described by the plot of stress versus cycles to failure (S-N diagram) shown in Figure 4.

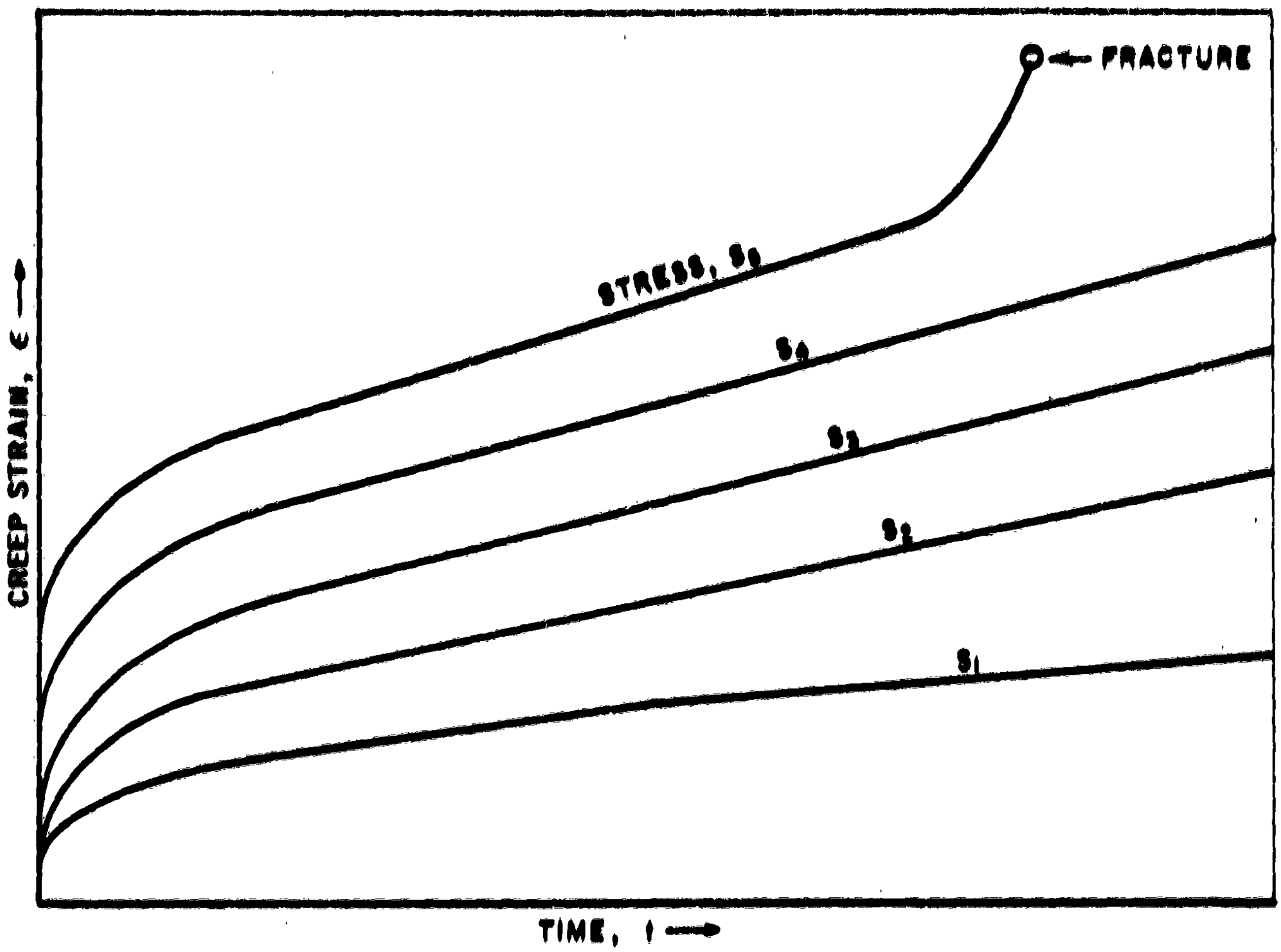

FIG. 3 CREEP-TIME CURVES IN TENSION FOR VARIOUS STRESS VALUES

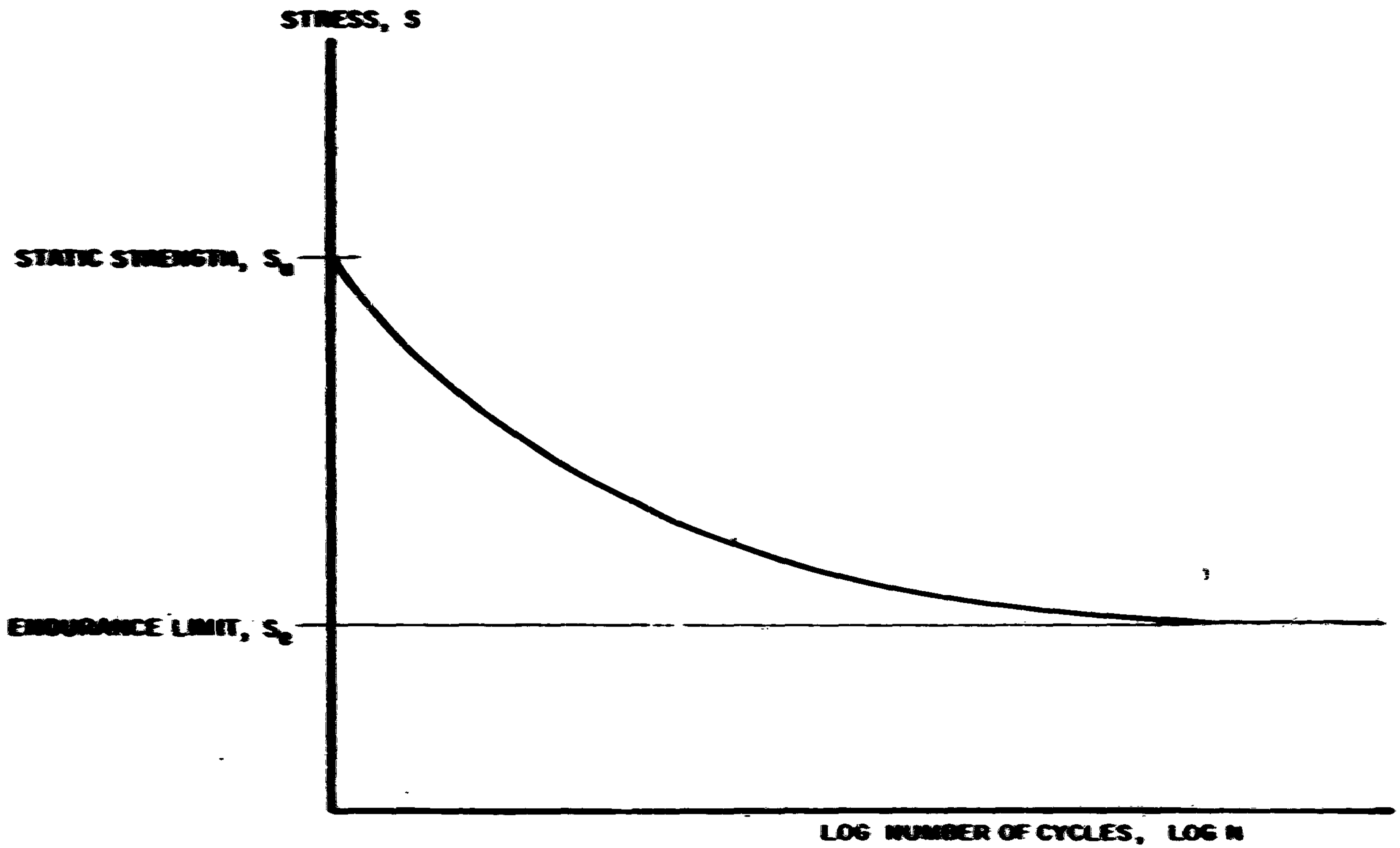

FIG. 4 TYPICAL S-N DIAGRAM

Most engineering materials exhibit an "endurance limit," which is the value of stress below which it is presumed that an infinite number of cycles are required to produce failure. In general the relationship may be described by:

$$N = k_1(s - s_e)^{-k_2} - k_3 \qquad (5)$$

where k_1, k_2, k_3, and s_e are emperical constants, s_e being the endurance limit. For sinusoidal loading, the stress may be described by

$$s = s_m + s_r \sin wt \qquad (6)$$

where s_m is the mean stress level and s_r is the variable stress illustrated in Figure 5. The effect of mean stress on fatigue failure at a specified number of cycles is illustrated by the Goodman diagram shown in Figure 6. This may be stated mathematically as. $\frac{S_r}{S_e} + \frac{S_m}{S_u} = 1.$ (7)

When a material is (' . . loaded at different stress levels, Miner's criterion may be employed to estimate the cumulative damage from fati... This states that a material will fail when the sum of the ratios of cycles, n, at each value of load to the cycles to failure, N, at the same load exceeds about 0.8 to 1.0:

$$\sum_{i=1}^{J} \frac{n_i}{N_i} \quad 0.80 \text{ to } 1.0 \qquad (8)$$

f. <u>Wear</u>

Wear occurs whenever materials rub over each other. The rate of wear is proportional to the product of normal contact load, N, and length of travel L, ' one part over the other, and inversely proportional to the

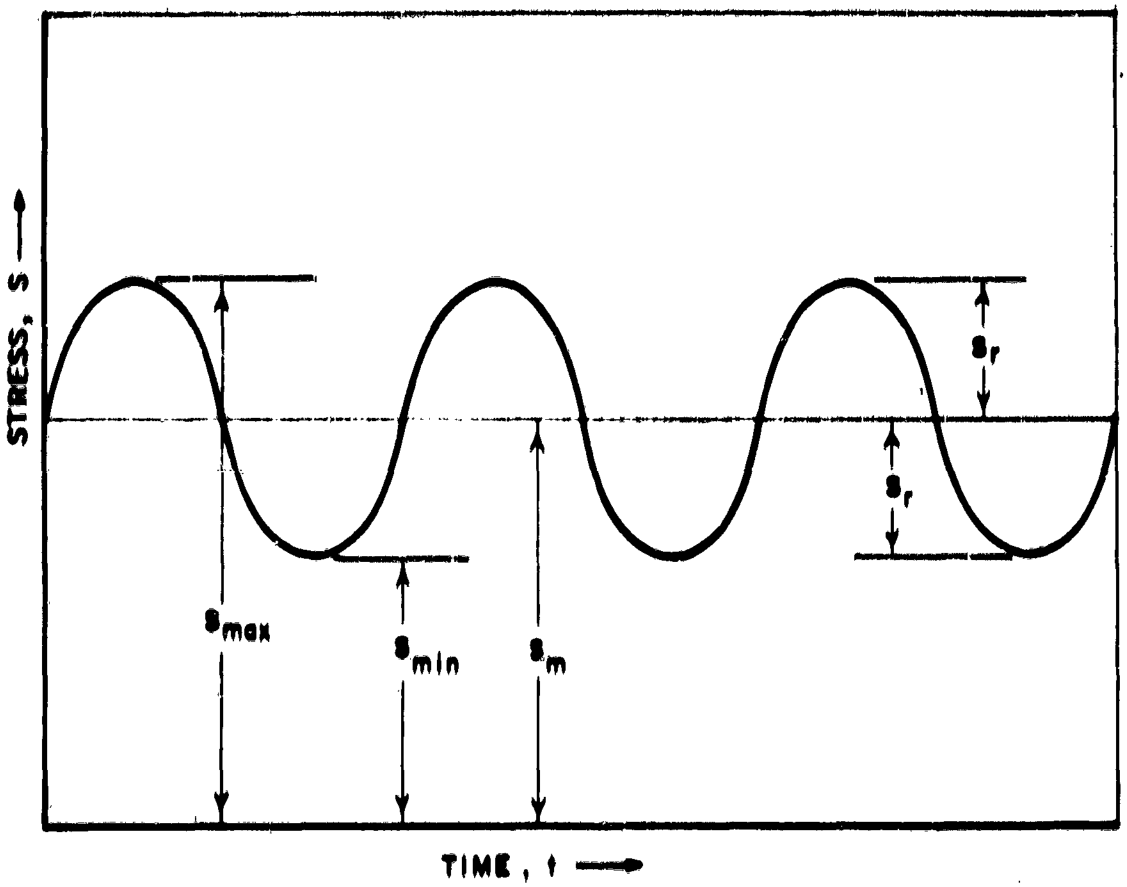

FIG. 5 STRESS-TIME VARIATION FOR FLUNCTUATING STRESS

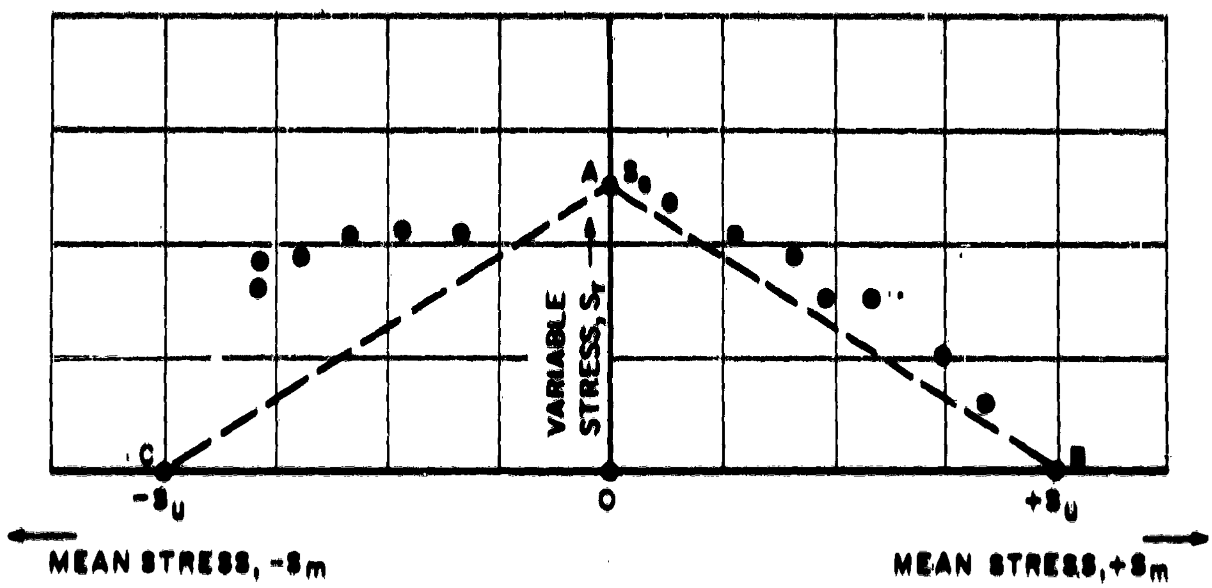

FIG. 6 INFLUENCE OF MEAN STRESS ON FATIGUE STRENGTH

hardness of the material, H.

$$\frac{dw}{dt} = k \frac{NL}{H} \tag{9}$$

Wear rarely causes breakage of a member, but rather failure is caused by parts becoming out of tolerance and not performing their required function satisfactorily.

g. <u>Corrosion</u>

Corrosion of a material is the gradual deterioration of the surface by chemical reaction with its environment. The type of corrosion most likely to occur in electromechanical military ground equipment is atmospheric corrosion. The metal combines with oxygen to form oxides which then usually flake, chip, or wear off relatively easily. Moist air commonly accelerates the process. Also, metals under stress tend to corrode more rapidly than if unstressed. Materials subjected to cyclic loads and corrosion may form pits which act as stress-raisers and hence greatly reduce the fatigue strength.

h. <u>Impact</u>

Impact strength may be considered to be the energy-absorbing quality or "toughness" of a material and implies a rapidly applied load. In general, increased rate of loading improves the strength properties of a material. Young's modulus, yield strength, ultimate strength and maximum deformation are usually all higher values. If, however, the impact is applied while the metal is below the transition temperature, ductility is reduced and failure may even be brittle in nature. It has been shown that a critical velocity exists above which fracture is assured.

For uniaxial tension, for example, this velocity is given by the relation

$$V = \int_{0}^{e_0} \frac{ds/de}{\rho} \, de , \qquad (10)$$

where e_o is the strain at maximum load, ds/de is the slope of the stress-strain curve, and ρ is the density of the material.

i. <u>Galling</u>

Galling implies the digging or gouging of the surface of one material by another. Materials in contact exert interfacial pressures on one another and create a stress distribution in the region. When the maximum stress exceeds the yield strength of one material the surface becomes permanently deformed. If relative motion is involved the surface is "galled." This phenomenon is based on a derivation by Hertz for the maximum interfacial pressure between two bodies in contact. If in the region of contact the radii of curvature are R_1 and R_2, the moduli of elasticity are E_1 and E_2, and the Poisson's ratios are u_1 and u_2, respectively, for the two materials, the maximum stress resulting from a contact force P is shown to be

$$S_{max} = \frac{1}{\pi} \left[\frac{6P\left(\frac{1}{R_1} + \frac{1}{R_2}\right)^2}{\frac{(1-u_1)^2}{E_1} + \frac{(1-u_2)^2}{E_2}} \right]^{\frac{1}{3}} . \qquad (11)$$

Galling occurs when $S_{max} > S_y$, where S_y is the yield strength of one material.

j. Sticking or slipping

Sticking occurs when parts in contact cease to have an intended relative motion. Slipping, conversely, occurs when parts in contact exhibit an unintended relative motion. Both effects are governed by the friction between the materials. If F is the tangential shear force applied at the interface and N is the normal force applied, the friction force is $f = \gamma N$ where γ is the coefficient of friction for the materials. Slippage occurs if $F > f_s$, and sticking occurs if $f_d > F$ where f_s and f_d are calculated using the static and dynamic coefficients of friction respectively. An important factor which affects the friction force is clearly the normal contact load N. This load is often a direct function of the temperature of the materials. Differential expansion or contraction of the parts increase or decrease N in a manner such that the external constraints on the two parts are satisfied.

k. Failure examples

A number of situations to illustrate the action of various mechanical failure mechanisms and failure modes will now be considered. For example, machine parts may fracture for many different reasons, but the actual fracture failure follows either of two basic modes:

1) Ductile or shear type of failure caused by excessive shear stresses and resulting in slip along crystallographic planes.

2) Brittle or normal type of failures caused by excessive normal stresses and resulting in separation of the crystals along planes normal to the maximum tensile stress.

The particular mode of failure that will prevail in any given application is the result of the comparative balance between two sets of opposing forces. On one hand are shear stresses opposed by resistance of the metal to slip. On the other are normal stresses opposed by cohesive or "tear apart" resistance of the metal. Which of the two systems of opposing forces is overbalanced first determines the mode of failure.

Some materials can fail in a ductile manner under one set of conditions and a brittle manner under another set. One of the most common materials exhibiting this phenomenon is mild steel which exhibits ductile characteristics if pulled in a simple tensile test but evidences a brittle fracture when subjected to fatigue loading or when severely notched. Another example is that of tool steels, which under pure torsion fail in a ductile manner, but under simple tension fail in a brittle manner. This case is illustrated in Figure 7. Where maximum shear stress is plotted as the ordinate and maximum normal stress as the abscissa, the critical shear stress, or the shear strength of the tool steel, is shown as A. Critical normal stress, or the tensile strength of the tool steel, is shown as B. The rectangular boundary based upon these two values represents the strength. When a machine member is subjected to a pure torsional load the maximum shear stress equals the maximum tensile stress. The line defining this loading condition will therefore take the slope of 1, or a 45 degree direction as shown. This line will intersect the critical shear stress boundary giving rise to a shear or ductile type of failure. On the other hand, if the same steel is subjected to simple tension, shear stress will equal one-half the tensile stress and the slope of the line will be one-half

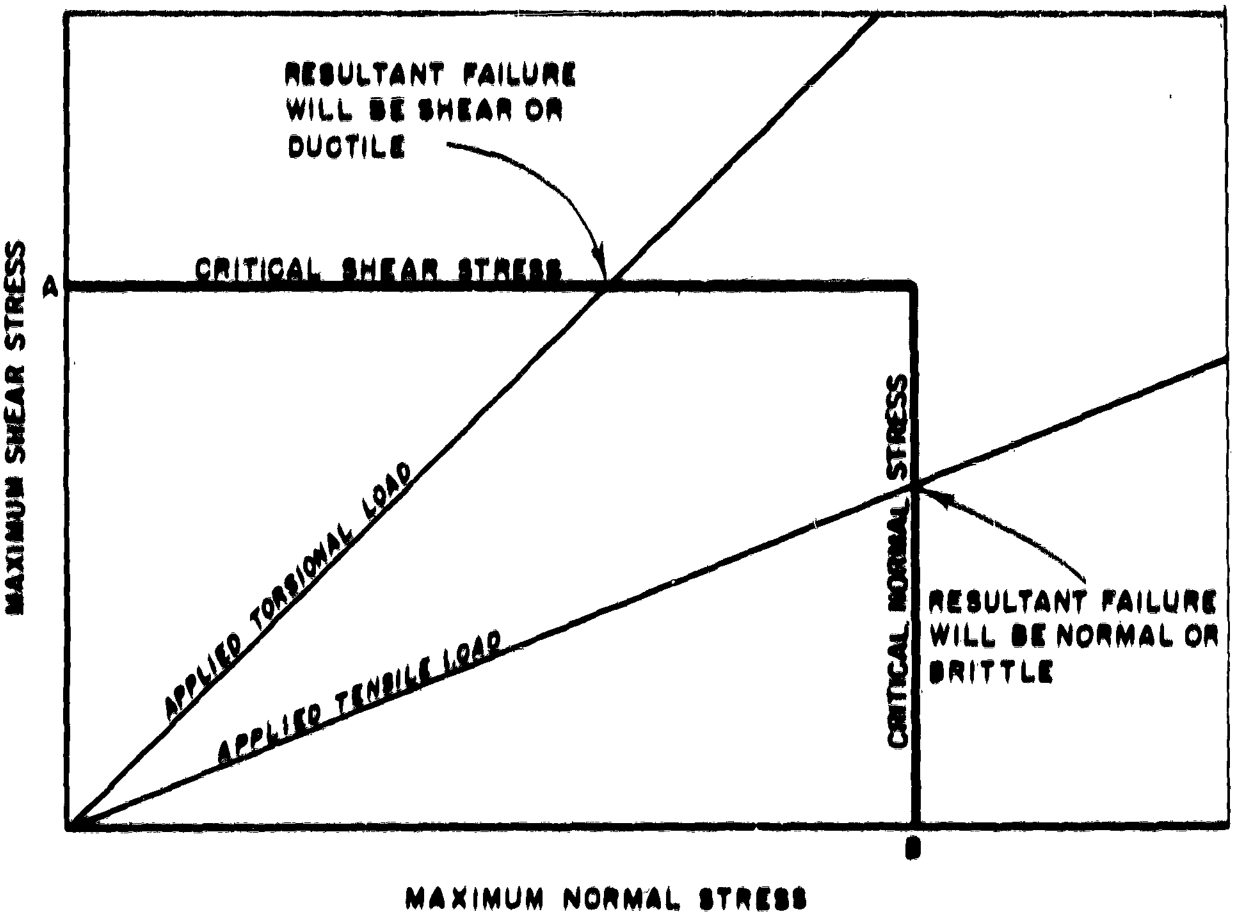

FIG. 7 EFFECT OF LOADING ON THE TYPE OF FAILURE
(From C. Lipson, Engineering For Reliability)

as shown. This line will intersect the critical normal stress boundary, and normal or brittle failure will occur. The particular rectangle shown in Figure 7 refers to tool steels. Similar rectangles can be drawn for other materials.

For each rectangle the mode of failure will in addition be determined by a variety of external conditions. These external conditions can be analysed for their effects on the mode of failure. The most important factors in determining which type of failure will take place are tabulated as follows:

External Factors Affecting Mode of Failure

a. Manner of loading, static or fluctuating
b. Range of imposed stresses
c. Number of load applications
d. Velocity of loading
e. Direction of stress (i.e. uniaxial or polyaxial)
f. Temperature during the load application
g. Geometry of the part (i.e. presence of stress concentrations, etc.)

Internal Factors Affecting the Mode of Failure

a. Material
b. Surface treatment of material

With regard to the manner of loading, it may be stated that a machine member which exhibits ductile properties under static loading will in general fail in a brittle fashion when the load is fluctuating. As the number of load applications increases, failure generally shifts from a ductile type of failure to that of a brittle type. Information taken from testing of many industrial products, of which a silent chain is an example,

indicates that transition from ductile to brittle failure generally appears to occur in the neighborhood of ten thousand cycles. Information such as this would indeed seem to indicate that it is important to have some knowledge of basic failure mechanisms when attempting to predict intelligently the mode in which device failure might occur.

Repeated stresses however, do not always result in a fatigue type of failure, because fatigue is affected by the range of stress and the number of applications. A variable stress other than complete stress reversal is caused by an alternating stress superimposed upon a steady stress. If the ratio of alternating stress to steady stress is relatively low, it may still be possible to have a yielding type of failure. If the number of cycles is low the failure may also fall within a plastic classification. Often there is no distinct line of demarcation, since the results are affected by the material and the stress history, previous amount of cold working, etc. Figures 8 and 9 indicate the effect of stress range on this particular failure mechanism.

Rate of loading is another important factor which determines whether a material will fail in a ductile or a brittle manner. A material that evidences ductile failures under simple tension at ordinary testing speeds may show brittle failure when loaded at a high rate. It should be noted however, that in notched impact tests such as the Sharpy test it is the presence of the notch and not the speed of loading which causes brittle fracture. According to laboratory tests, internal resistance to slip increases directly with the velocity of deformation, but resistance to normal separation is not similarly affected, although Zinc, for example, will bend with marked ductility under sudden loading.

STATIC TENSILE PROPERTIES OF AN ANNEALED AND COLD WORKED 0.29% CARBON STEEL		
STEEL	YIELD STRESS* S_y	TENSILE STRENGTH
▣	34,800 psi	64,600 psi
△	64,400 psi	76,600 psi
⊙	76,000 psi	87,200 psi

*BASED ON 0.10% PERMANENT SET

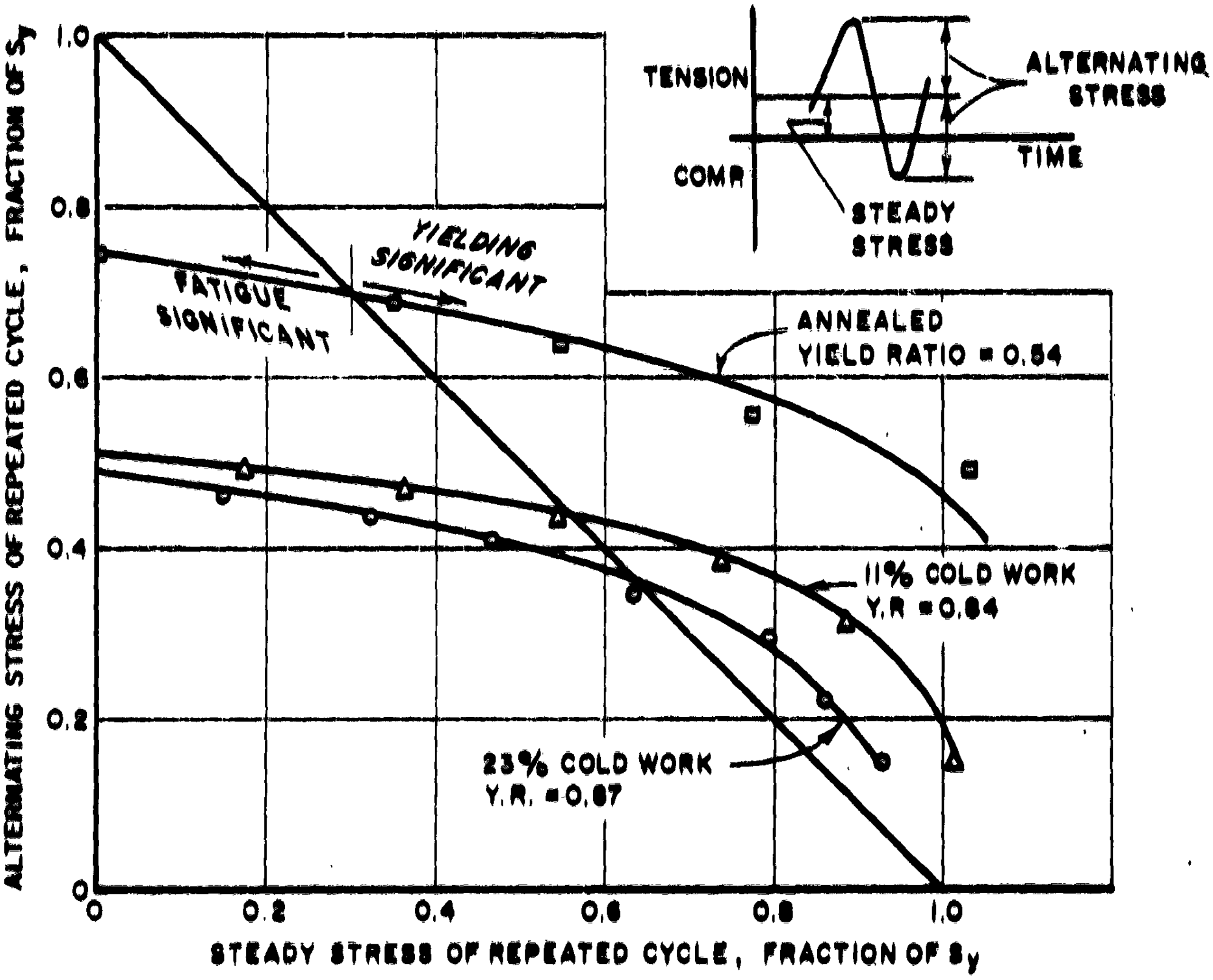

FIG. 8 EFFECT OF STRESS RANGE ON MODE OF FAILURE FOR LOW-STRENGTH STEEL
(From Lipson)

STATIC TENSILE PROPERTIES OF HEAT-TREATED STEELS		
STEEL	YIELD POINT S_y	TENSILE STRENGTH
□	125,400 psi	200,900 psi
×	91,100 psi	111,800 psi
○	108,700 psi	123,300 psi
△	153,000 psi	162,000 psi

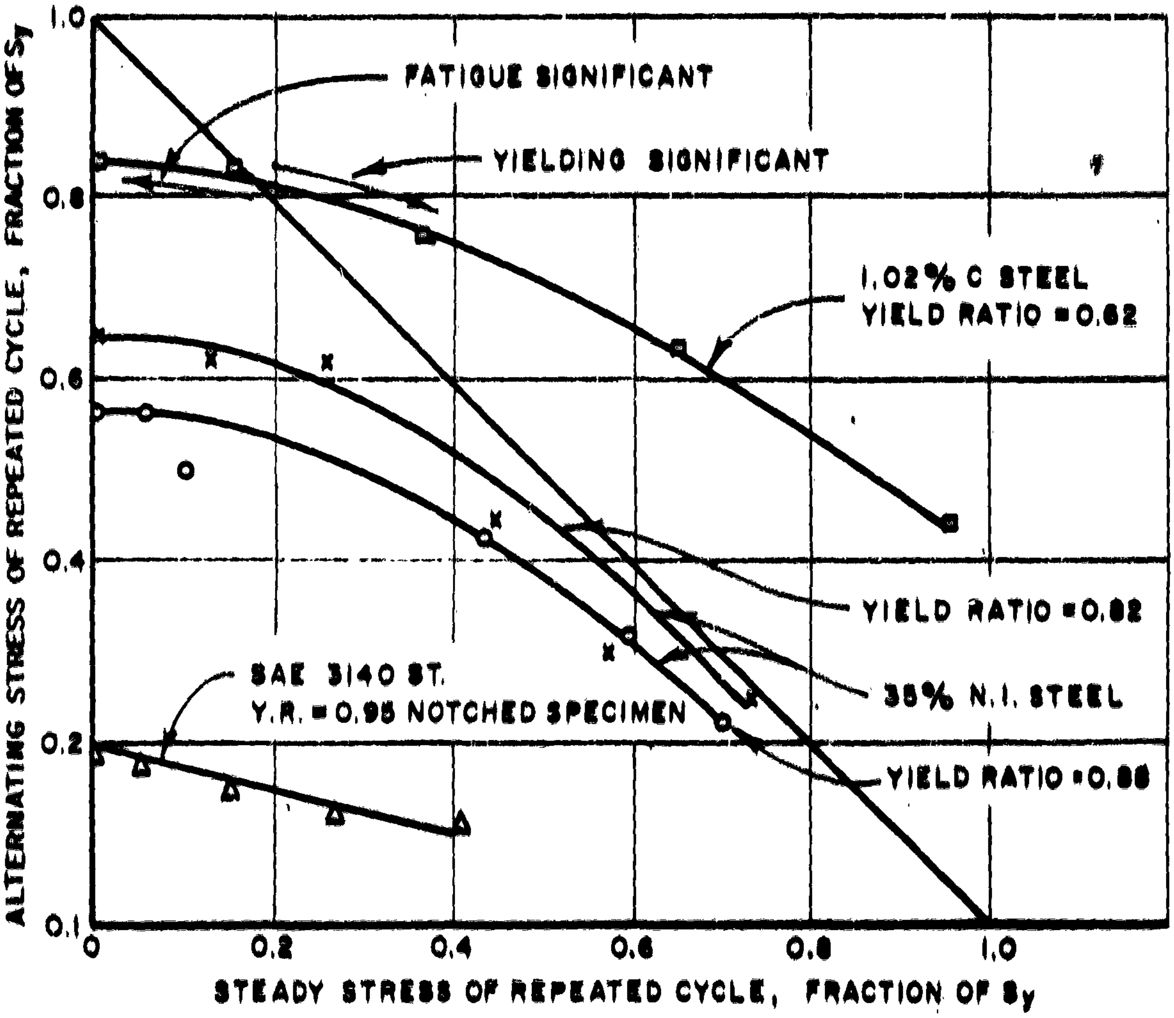

FIG. 9 EFFECT OF STRESS RANGE ON MODE OF FAILURE FOR HIGH-STRENGTH STEELS (From Lipson)

In regard to the direction or type of stress, preceeding examples have shown how a ductile material can fail in a brittle fashion. An example of how a brittle material can be made to show plasticity is given by Von Karman. He demonstrated that marble, when subjected to a purely hydrostatic or polyaxial state of stress, would deform plastically instead of crumbling as it would under uniaxial compression.

The opposite effect is found in a simple tensile test of mild steel. Upon examination a fracture of this type will be found to be made up of a flat central area with surrounding conical head which is illustrative of central cohesive failure and external ductile failure. During the pulling process the tensile specimen necks down, whereby the stresses change from uniaxial to triaxial. The result is a cohesive fracture in the core which continues outward until completion of shear failure in the outer area.

The geometrical shape of a particular machine component has a marked effect upon the stress distribution, which in turn has a marked effect upon the failure mechanism. Any discontinuity in material or sudden change in shape of a machine member can cause local triaxial stresses and may alter the type of fracture from plastic to brittle by increasing the normal stresses and reducing the shear stresses. This may occur microscopically because of inclusion and initiate a crack that will lead to a brittle fracture under fatigue loading. It may also happen on a macroscopic level resulting from a sudden change in the diameter of the piece, such as a severely necked bar, and cause a brittle fracture (i. e., a large stress concentration factor). Any stress concentration factor such as a notch, sharp tool mark, pitting or change in section can effect the condition of stress and therefore the mechanism of failure. Figure 10 is a graphical

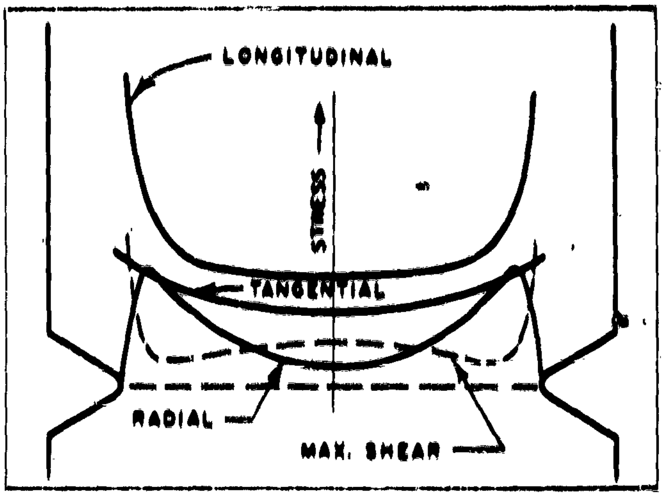

FIG. 10 VARIATION OF STRESS ACROSS A NOTCHED CYLINDER SUBJECTED TO TENSION
(From Lipson)

representation of the 3 dimensional stress system in a notched bar under tension.

The temperature of metal during loading appears to affect its resistance to slipping. In general resistance to slipping increases with low temperature and decreases with high temperature. It is clear, therefore, that a brittle fracture can be produced in a tougher material by lowering the temperatures sufficiently, so that cohesive forces are overcome under load before slip resistance breaks down. However, under elevated temperatures a plastic flow may take place at stresses considerably below the conventional yield point, because resistance to internal slip is lowered.

Another factor which may be considered is that of surface treatments introducing residual compressive stress on the surface of a part. This compressive stress counteracts tensile stress resulting from the externally applied load, thus reducing the probability of a cohesive failure. In this category of surface treatments belong such processes as shot peening, carbeurising, induction hardening, and nitriting. It will be noted, however, that surface-treated parts can develop failures originating either at the surface or below the surface, depending upon the type of applied loading and the severity of stress concentrations.

3. <u>Conclusions from mechanical failure mechanisms study</u>

The study of mechanical failure mechanisms was undertaken to determine to what extent a reliability prediction method based upon such information could be formulated. For this program such an approach would not be the most effective one. Two of the factors leading to this conclusion come from a study of the nature of the failure mechanism data

presently available. The first is that, although a seemingly considerable amount of information is available for a number of different mechanical mechanisms, it is, to a large degree, of a qualitative nature. The second factor is that, even where relationships may be available for describing particular failure mechanisms, there is no generally applicable theory connecting these relationships so as to provide a unified approach for the entire spectrum of such mechanisms.

In certain specific areas empirical equations coupled with specific experimental results do represent the observed phenomena with a good degree of accuracy. These cases are by no means representative of the field in general. Two areas may be contrasted as an example of this situation. On one hand, fatigue probably represents the best understood failure mechanism. Because of the dynamic nature of the fatigue problem and its application to part-strength analysis for automated equipment, it has received a great deal of attention. However, even in this well studied area, many facets of the problem lack quantitative analytical expressions which adequately represent the observed phenomena. An example is the area of cumulative damage criteria where at least four theories have been advanced to explain the phenomena, but all are only partially able to do so. The study of friction and wear failure represents an even worse situation. Here little evidence of any broad applicable descriptive theory can be found.

4. Selected approach for mechanical prediction

This evaluation of mechanical failure mechanisms, together with further study into the mechanical prediction problem, indicated that a more useful approach would be to handle the mechanical aspect from what will be called the functional module level. The module concept spoken of here

serves to classify a mechanical device or array of components according to the function it performs, rather than according to its actual physical makeup. As an example, consider an electro-mechanical-hydraulic system whose function is to remotely drive an aircraft control surface. The net function performed by the components making up the module considered here is that of positioning. The consideration of the mechanical aspect at this level has a number of desirable features. All modules performing the same function may be studied as a family, even though they will contain different components or configurations internally. It is also possible that modules from the same family may tend to exhibit similar outward failure modes and patterns, rather independently of the components contained within. By considering mechanical devices at this level, better utilization can be made of the existing mechanical reliability data, particularly field data, which is often apparently of a gross nature. Clearly, selection of this direction implies greater emphasis upon generality, with a resulting constraint upon precision for any specific situation.

After determining suitable module configurations, deterministic relationships must be derived describing the output of the module in terms of its internal characteristics (transfer function), pertinent environmental factors, and time. Taking into account the random nature of those factors influencing the operation of the module, a transformation can be made from a deterministic model to a probability model which will then give some description of the reliability characteristics of the module. This transformation to a probability model will actually involve determining the parameter values of a statistical distribution function. Techniques presently exist and are being developed for this task. The major problem lies in the development

of the deterministic model for a module. It should be noted that neither individual component characteristics, nor the field of mechanical failure mechanisms which was previously discussed in some length, will be ignored. Both areas can provide valuable inputs toward the development of the deterministic model. Also, the electronic portion of an electro-mechanical system will not necessarily be excluded in the formulation of such modules. The extent to which the electronic area will be integrated with the mechanical for prediction purposes, and to what extent they will be considered separately, will also be one of the outputs of the program.

D. Program Plan

In view of the above considerations for an approach to the mechanical reliability prediction problem during the first quarter of the program, an updated phase outline for the remainder of the program is presented below.

Program Outline

1. Study and evaluation of the electronic reliability area, and general reliability prediction techniques.
2. Development of functional module concept from equipment studies.
3. Evaluation and mathematical modeling for module.
4. Transformation into module probabilility model.
5. Electro-Mechanical interface considerations (combining predictions from both areas).
6. Physical model considerations, design and test of model, followed by evaluation of data and incorporation into prediction technique.
7. Implementation of technique for general use in making reliability predictions

E. Bibliography

The following bibliography contains a listing of documents surveyed and utilized thus far in the program. The listing is divided into three areas: A listing of general reliability documents including those utilized in the survey of mechanical failure mechanisms, a listing of SCL technical requirements documents acquired from the Signal Corps, and a listing of Army Technical Manuals acquired from the Signal Corps. The items in the latter two areas are being utilized in the survey of Signal Corps' equipment.

I. Reliability References

1. Westergaard, H. M., Theory of Elasticity and Plasticity, Harvard University Press, Cambridge, Mass., 1952

2. Timoshenko, S., Theory of Elastic Stability, McGraw-Hill Book Company, Inc., New York, 1936

3. Moore, H. F., Materials of Engineering, McGraw-Hill Book Company, Inc., New York, 1947

4. Marin, J., Mechanical Behavior of Engineering Materials, Prentice-Hall, Inc., Englewood Cliffs, N.J., 1962

5. Hill, R., The Mathematical Theory of Plasticity, Oxford University Press, London, 1956

6. Lipson, C. Engineering for Reliability University of Michigan, 1962

7. Moskowitz and McLean, Some Reliability Aspects of System Design 1955 OTS Document PB 118407

8. Earles, D. R. and M. F. Eddins, Failure Rates, Failure Mechanisms, Reliability Physics (The Physics of Failure), and Failure Criteria (4 volumes), Reliability Engineering Data Series, April, 1962 Avco Corporation, Wilmington, Mass.

9. Pieruschka - Mathematical Foundation of Reliability Theory, 1958 OTS Document PB 134700

10. Symposium: Military Electronics Reliability and Maintainability Vols. I, II, III, IV
Rome Air Development Center
Griffiss Air Force Base, N. Y.
OTS Document PB 140078

11. Epstein, Statistical Techniques in Life Testing, Chapter III. Problems of Estimation 1959
Wayne State University
Detroit, Michigan
OTS Document PB 144401

12. Calvert, Some Notes on the Estimation of Reliability, 1956 OTS Document AECU 3425

13. Clark, Reliability Studies of Systems in Which Component Reliabilities Vary with Environment, 1955
Sandia Corporation
OTS Document AECU 3312

14. University of Michigan Engineering Conference
Engineering Applications of Reliability - technical papers, 1962

15. Schneider, L. L. Mechanisms of Failure
Reliability Engineering Associates
Skokie, Illinois

16. Eisenlohr, G. M. and Willoughby, W. J., A Theoretical Technique for Predicting the Reliability of Solenoid Waves, 1962
ARINC Research Corporation
Washington, D. C.

17. Lusser, R. Predicting Reliability, 1957
Research and Development Division of Ordnance
Missile Laboratories
Redstone Arsenal
Huntsville, Alabama

18. Doshay, I., Reliable Spacecraft Designs, 1961
Society of Automotive Engineers
Paper 343 B

19. Wright, D. S. A Review of Electron Tube Reliability, 1961
Engineering Data Release
The Bendix Corporation - Red Bank Division
Eatontown, N. J.

20. Fulcher, C. W. G., Failure Prediction for Nonmaintainable Electronic Components
General Electric Company
Defense Systems Department
King of Prussia, Pa.

21. Donaldson, J. S., Reliability Analysis and Prediction - Independent of Distribution, 1960
Vought Electronics Division

22. Donaldson, J. S. and Helden, F. K., A Reliability Analysis and Prediction Technique Applicable to Electronic and Non-Electronic Systems, 1962
Timco Electronics Division
Ling-Timco-Vought, Inc.

23. Plait, A. The Weibull Distribution
Reliability Engineering Department
The Magnovox Company

24. Lusser, R. The Notorious Unreliability of Complex Equipment, 1958
Astronautics

25. Shube, E. Ball-Bearing Survival
Machine Design, July 19, 1962

26. Stevens, K. Basic Reliability Test Categories
Test Engineering, September 1962

27. Weiss, H. Estimating Experimental Errors
Machine Design, June 7, 1962

28. Horne, R. C., Jr. Reliability of the AN/APS-20E Radar System, 1959
ARINC Research Corporation
Washington, D. C.
ARINC Document No. 101-11-139

29. Scott, S. R. Techniques of System Reliability Measurement, Vol. I and II, December 1958
ARINC Research Corporation
Washington, D. C.
ARINC Document No. 101-6-129

30. Electronics and Electrical Reliability Handbook, 1959
Martin
Baltimore, Md.

31. Proceedings of the Symposium on the Physics of Failure in Electronics
Technology Center
Chicago, Illinois, September 1962

32. Reliability Theory and Practice - A course sponsored by the U.S. Army Signal Research and Development Laboratory
ARINC Research Corporation
Washington, D. C.

33. Proceedings of the IAS National Symposium on Tracking and Command of Aerospace Vehicles
San Francisco
California February 1962

34. Supplier Reliability Guide
Aero-Space Division
Boeing Airplane Company
Seattle, Washington

35. Proceedings of the IAS Aerospace Systems Reliability Symposium
Salt Lake City, Utah April 1962

36. Lusser, R. Production Environment Testing, November 1957
Research and Development Division
Ordnance Missile Laboratories
Redstone Arsenal
Huntsville, Alabama

37. McNorton, T. L., Teitelbaum, B. R.
Research on "Super" Non-Electronic Components
Flight Control Laboratory
Aeronautical Systems Division
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio
Technical Report No. ASD-TDR-62-27

38. Earles, D. R. Reliability Application and Analysis Guide 1961
ASTIA AD No. 262390

39. Winter, A. N. Missiles and Electronics Mechanical Reliability Manual July 1959
MARTIN
Baltimore, Maryland

40. Project Syncom: Satellite Communications Transportable Ground Terminal Design Plan Volume VI Reliability 8 June 1962
Prepared for U.S. Army Signal Research and Development Laboratory
Fort Monmouth, N.J.
by The Bendix Corporation
Baltimore, Maryland

3. Signal Corps Technical Requirements

1. Signal Corps Technical Requirement SCL-4328 15 September 1961
Computer Set Digital Data MOBIDIC-D

2. Signal Corps Technical Requirement SCL-4372 1 May 1962
Computer Fielddata-Typewriter Set

3. Signal Corps Technical Requirement SCL-4330 15 September 1961
Amendment No. 1, 2 March 1962
Formant Tracking Vocoder System

4. Signal Corps Technical Requirement SCL-4341 1 November 1961
Amendment No. 1 2 May 1962
Recorder - Reproducer Set Sound AN/UNH-10

5. Signal Corps Technical Requirement SCL-4342 30 October 1961
Tactical, Digital, Voice Communications System

6. Signal Corps Technical Requirement SCL-4067 28 October 1958
Amendment No. 2, 13 March 1962 Superseding Amendment No. 1
1 September 1960
Converter, Telegraph Signal

7. Signal Corps Technical Requirement SCL-4269 5 September 1960
Amendment No. 1 20 February 1961
Involved Phase Modulator Demodulator

8. Signal Corps Technical Requirement SCL-4273 27September 1960
Amendment No. 1 15 June 1962
Synchroniser, Electrical SN-293( )/G

9. Signal Corps Technical Requirement SCL 4284 29 November 1960
Amendment No. 3 4 December 1961 Superseding Amendment No. 2
14 November 1961
Multiline Monitor Equipment

10. Signal Corps Technical Requirement SCL 4369 30 November 1961
Improved Center-Fed Antenna

11. Signal Corps Technical Requirement SCL-1938A 22 June 1960
Amendment No. 1 19 April 1961
Computer Set, Digital Data, General Purpose AN/TYK-7(U)

12. Signal Corps Technical Requirement SCL-1891B 19 August 1958
Superseding SCL-1891A 18 November 1957
Telephone Signal Converter TA-375( )/TTC and TA-376( )/TTC
(formerly 4-wire Automatic Converter)

13. Signal Corps Technical Requirement SCL-4026B 17 August 1961
Amendment No. 1 14 June 1962
Radio Link Group, Sound and Flash Ranging AN/TRA-26( )

14. Signal Corps Technical Requirement SCL-4222 28 March 1960
Radio Set AN/GRC-50( )

15. Signal Corps Technical Requirement SCL-4223 6 October 1960
Superseding SCL-4223 28 March 1960
Regulator, Voltage CN-514( )/U

16. Signal Corps Technical Requirement SCL-4228A 5 December 1961
Superseding SCL-4228 5 April 1960
Photoflash System for Night Photographic Surveillance

17. Signal Corps Technical Requirement SCL-4249 22 July 1960
Computer Set, Digital Data, General Purpose, AN/ TYK-( )

18. Signal Corps Technical Requirement SCL-4250 8 June 1960
Universal Power Supply

19. Signal Corps Technical Requirement SCL-4256 25 August 1960
Generator Direct Current G-54( )/U (Hand Cranked)

20. Signal Corps Technical Requirement SCL-1759D 2 November 1961
Superseding SCL-1759C 24 March 1961
Telephone Set TA-341(XC-2)/PT

21. Signal Corps Technical Requirement SCL-4094A 1 March 1961
Typed Page Reader (AN/FST-6)

22. Signal Corps Technical Requirement SCL-5767 19 February 1960
Addendum D 17 March 1961
Short Range Surveillance Radar Set

23. Signal Corps Technical Requirement SCL-4300 10 May 1961
Amendment No. 1 1 July 1962
Variable Speed Recorder Reproducer

24. Signal Corps Technical Requirement SCL-4304A 30 November 1961
Superseding SCL-4304 18 May 1961
Printer, Projection, Photographic EN-36( )

25. Signal Corps Technical Requirement SCL-4307 9 June 1961
Signal Generator AN/URM-123( )

26. Signal Corps Technical Requirement SCL-4309 14 August 1961
Telephone Signal Converter CV-905( )1G

27. Signal Corps Technical Requirement SCL-4310 27 November 1961
<u>Fieldata Digital Magnetic Tape Transport, - Pneumatic Drive, Computer Type</u>

28. Signal Corps Technical Requirement SCL-4314A 30 November 1961
Superseding SCL-4314 16 October 1961
<u>Darkroom, Photographic, Portable ES-29( )</u>

29. Signal Corps Technical Requirement SCL-4317a 30 November 1961
Superseding SCL-4317 -16 October 1961
<u>Processing Machine, Photographic Film and Paper EH-29( )</u>

3. Army Technical Manuals

1. Department of the Army Technical Manual TM 11-2229 June 1957
Teletypewriters TT-47A/UG, TT-48A/UG, TT-69A/UG, TT-70A/UG

2. Department of the Army Technical Manual TM 11-5815-264-35 8 Dec 61
Field and Depot Maintenance Manual
Teletypewriters TT-343/ G and TT-347/FG

3. Department of the Army Technical Manual TM-11-5840-260-12 6 Apr 62
Operator and Organizational Maintenance Manual
Antenna Group OA-1227/TPS

4. Department of the Army Technical Manual TM 11-5840-259-14 Oct 61
Operator, Organizational and Field Maintenance Manual
Radar Set AN/MPQ-29( )
(Research and Development Model)

5. Department of the Army Technical Manual TM 11-517 December 1956
Radio Set AN/ARC-44

6. Department of the Army Technical Manual TM 11-6615-204-12 30 Aug 60
Operators and Organizational Maintenance Manual
Automatic Flight Control System AN/ASW-12(V)

7. U.S. Army Signal Corps
Instruction Manual for Telephone Set TA-341/PT

8. Instruction Book 311A Electronic Data Printer Model 311
Volume 1:Text
Kleinschmidt Division of Smith-Corona Marchant Inc.

9. Instruction Book 311A Electronic Data Printer Model 311
Volume 2:Illustrations
Kleinschmidt Division of Smith-Corona Marchant Inc.

V. CONCLUSIONS

The initial effort in the program has been directed toward determining the most suitable technique for handling the mechanical reliability prediction task. The investigation indicated that prediction effort centered on the failure mechanism level would have the disadvantages that the larger portion of knowledge on failure mechanisms is either empirical or of a qualitative nature. In addition, there is presently no generally applicable theory connecting these relationships so as to provide a unified approach for the entire failure mechanism spectrum.

The prediction approach which has evolved from the studies carried out during the first quarter utilizes the concept of the functional module. By dealing with the reliability prediction problem at this level, a more general, though probably less precise approach is taken to the problem, while still allowing the use of certain failure mechanism concepts where they would be most useful.

VI. PROGRAM FOR NEXT QUARTER

During the next quarter the portion of the literature search concerned with electronic reliability information, which was started late in the first quarter, will be completed. From this search a detailed review will be made of available electronic failure data and its applicability to this program. In addition, a study will be started on failure distributions and statistics for electronic, electro-mechanical, and mechanical parts.

A detailed mail survey of the country's largest manufacturers of mechanical components will be initiated. The companies will be chosen on the basis of their manufacturing mechanical components and/or modules similar to those selected as being typical of those found in Signal Corps' equipments. Information will be requested concerning the results of any life tests, and any data on failure rates, expected life, failure modes, and operational stresses.

A detailed review will be made of Signal Corps' technical literature for the purpose of catagorizing both the electronic and mechanical components within various equipments. From this study, the functional modules, which will form a basic part of the reliability prediction technique, will be formed, and their characteristics will be studied. This study of the modules will provide information toward determining the parameters for the failure distribution functions of the modules being studied. Investigation will also be started on probability distribution functions which will form a part of the prediction technique.

VII. TECHNICAL PERSONNEL

The list below indicates the ARF staff members who have taken part in the work covered by this report, including the man-hours of effort contributed by each person during the quarter. The following pages present the background and experience of the ARF staff members presently assigned to the project.

Name	Hours of Effort for First Quarter
Darwin F. Simonaitis, Project Engineer	352
Thomas L. Bush	112
Carlton E. Gebhart	132
Morton E. Goldberg	50

BUSH, THOMAS L.

TITLE:	Research Engineer, Applied Mechanics
EXPERIENCE:	Mr. Bush has over eight years of experience in engineering design and analysis. His early experience was in the design of automatic high-speed machinery for handling and processing paper and plastic films, and in packaging equipment for the food industries. Since joining Armour Research Foundation, he has participated in, and directed projects concerned with the development of high "g" and vibration tolerant packaging for electronic components, dynamic and vibration analysis of various materials-handling systems and automatic test equipment. His background also includes undergraduate teaching in Mechanical Engineering at Illinois Institute of Technology.
PUBLICATIONS:	"A Mechanized Live Animal Transport System for Packing Houses." Second place in 1961 Chicago Section A.S.M.E Prize Paper Contest.
EDUCATION:	B.S. in mechanical engineering, Illinois Institute of Technology. Completed course requirements for M.S. in Mechanical Engineering at same institution.
AFFILIATIONS:	A.S.M.E Pi Delta Epsilon

GEBHART, CARLTON E.

TITLE: Associate Engineer, Applied Mechanics

EXPERIENCE: Mr. Gebhart's experience prior to joing Armour Research Foundation was in the field of stress analysis of military electronic equipment for aircraft, missiles, and satellites. He has been responsible for the structural adequacy of such devices as microwave antennas, and infrared seekers and guidance heads. In that capacity, he became familiar with the problems resulting from extreme thermal, vibration, and shock requirements.

Since joining the staff at the Foundation, Mr. Gebhart has been engaged in projects concerning the mechanics of rigid and deformable bodies.

PUBLICATIONS: "The Effect of Forces and Pressures as a Cause of Coning on a Face Seal Used in the Pratt and Whitney J-75 Engine," Bachelor's Thesis, Department of Mechanical Engineering, M.I.T., January 1959.

"Bending of Symmetrically Loaded Circular Plates With Arbitrary Creep Characteristics," Master's Thesis, Department of Engineering, University of California, May 1961.

EDUCATION: B.S. in Mechanical Engineering from the Massachusetts Institute of Technology

M.S. in Engineering from the University of California at Los Angeles under a Hughes Master's Fellowship.

AFFILIATIONS: Pi Tau Sigma

GOLDBERG, MORTON E.

TITLE: Manager, Reliability and Components

EXPERIENCE: Mr. Goldberg has been with the Foundation since 1955. He has had direct responsibility for a number of research programs in the areas of determining and improving equipment and component reliability. These studies included the following: behavior of electron tubes during exposure to severe vibration, and design of standard vibration tests; redesign of subminiature R. F. connectors to improve reliability; reliability enhancement of rotary selector switches; evaluation of printed circuit solder joints; reliability determination of resistors and silicon rectifiers subjected to electrical and temperature over-stress conditions; and analysis of nuclear radiation damage in semiconductors. He has supervised programs including those dealing with investigations of wire and cable for aircraft and missile applications, electromagnetic and electrostatic accelerators and underwater arcing phenomena. Systems studies include programs directed toward the establishment of system availability, determination of information retrieval and analysis of reliability in terms of changes in system errors, and reliability and life expectancy analysis of complex electromechanical systems. He is currently in charge of a program directed toward determining device reliability through analysis of its mechanisms of failure. Prior to joining the Foundation, he was associated with a manufacturer of special-purpose capacitors for more than one year, and with a firm engaged in the development of industrial process control systems for more than four years.

TECHNICAL PAPERS: "Failure Theory as An Achilles Heel of Reliability Policies," Proceedings of the Second Annual Bay Area Reliability Seminar, May, 1960, co-authored with R. M. Bergslien and G. T. Jacobi.

EDUCATION: B.S. in electrical engineering, 1950, Illinois Institute of Technology; M.S. in electrical engineering, 1958, Illinois Institute of Technology.

AFFILIATIONS: Institute of Radio Engineers
Tau Beta Pi (Engineering)
Eta Kappa Nu (Electrical Engineering)
Sigma Iota Epsilon (Professional)

OTHER PROFESSIONAL DATA: Member of Electronic Industries Association Military Electronic Systems (M5) Committee, and Military Reliability (M5.2) Subcommittee.

Co-Chairman, Symposium on the Physics of Failure in Electronics, Chicago, Sept. 1962.

SIMONAITIS, DARWIN F.

TITLE:	Assistant Engineer, Reliability and Components
EXPERIENCE:	Mr. Simonaitis joined the Foundation in 1959. He has experience in the design and evaluation of a number of electrical components, including RF connectors, design of electrical safety devices, and design and evaluation of vibration tests for vacuum tubes. He has conducted an assessment of system effectiveness of a large scale data acquisition, processing and transmission system, and has carried out an error and reliability analysis for a large scale data processing system for use on research and exploration of space environments. His most recent activities have included an investigation of wire and cable and their requirements for aircraft and missile applications, a study of breakdown and corona phenomena at high altitudes, an evaluation of electrostatic generator concepts for high voltage applications in spacecraft, design of high voltage switching circuits, and a study of dry-circuit measurements for electrical contacts.
EDUCATION:	B.S. in electrical engineering, 1959, Illinois Institute of Technology M.S. in electrical engineering, 1961 Illinois Institute of Technology
AFFILIATIONS:	Tau Beta Pi (Engineering) Eta Kappa Nu (Electrical Engineering)

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